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POST IMPACT BEHAVIOR OF MOBILE REACTOR CORE CONTAINMENT SYSTEMS

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SUMMARY

In the future, nuclear assemblies containing fission products will be transported at high speeds. An example is a reactor supplying power to a large subsonic airplane. In this case an accident can occur resulting in a ground impact at speeds up to 1000 fps.

One method for containing fission products is to put the radioactive material in a containment vessel and design the vessel and its contents to absorb the impact energy without rupturing the vessel. After impact the heat from the decay of fission products must be transferred through the containment vessel wall and radiated, and convected to the surrounding environment even when the containment system is partially buried.

This paper analyzes the containment vessel temperatures after impact and attempts to understand the design variables that affect the post impact survival of the system. The heat transfer analysis includes conduction, radiation, and convection in addition to the core material heats of fusion and vaporization under partially burial conditions. Also, included is the fact that fission products vaporize and transport radially outward and condense on cooler surfaces, resulting in a moving heat source. A computer program entitled "Executive Subroutines for Afterheat Temperature Analysis" (ESATA) was written to consider this complex heat transfer analysis.

Seven cases were calculated of a reactor power system capable of delivering up to 300 MW of thermal power to a nuclear airplane. The results are

(1) The time required to reach the peak containment vessel temperature following the impact event could be in excess of 445 hours.

(2) The maximum peak containment vessel temperature calculated was 1660° F on the buried portion for the 300 MW, 50% burial, 60% fission product redistribution case.

(3) Lowering the reactor power level from 300 to 100 MW results in a 400° F decrease in the temperature of the buried portion of the containment vessel.

INTRODUCTION

The safety of large stationary and shipboard nuclear powerplants has been a primary design consideration for many years. In the future small nuclear powerplants may be used as a power source for mobile applications. Examples are reactors supplying power to aircraft and ground transportation vehicles.

In most of these cases an accident can occur which will result in a ground impact at speeds in excess of 1000 fps. If the impact is against a hard surface such as concrete or granite the reactor will undergo very high deceleration forces. The result will be structural failure of the coolant system and fracture of the cladding on the fuel elements (refs. 2, 3, and 4). Even under these accident conditions the fission products must be contained, i.e., not allowed to be released into the surrounding environment.

One method for containing fission products under these severe accident conditions is to put the nuclear reactor in a containment vessel and design the vessel and its contents to absorb the impact energy without rupturing the vessel. Gross deformation will occur in the case of impacting a hard surface. In the case of impacting soft ground the deformation will be less but partial or complete burial of the containment vessel may occur.

After impact the heat from the decay of the fission products must be dissipated. With the loss of the coolant system the heat must be transferred through the containment wall and dissipated via natural convection and radiation from the surface of the impacted containment vessel.

This paper analyzes the containment vessel temperatures after impact. The heat transfer analysis within the containment vessel includes conduction, radiation, and convection in addition to the core material heats of fusion and vaporization. Also included is the fission products vaporizing, transporting radially outward and condensing on cooler surfaces resulting in a moving heat source. The analysis treats the containment vessel system as lumped components, i.e., it does not mock-up valves, ducts, and containment system penetrations, etc.

The remainder of this report examines the impact event and describes the containment vessel system after impact under partial burial conditions. A parametric heat transfer analysis is conducted on the post impact configuration to determine the amount of heat that can be dissipated without melting or rupturing the containment vessel. The configuration analyzed is that of a containment vessel of varying degrees of ground burial in the undeformed state. The undeformed state was chosen

as a limiting case that better represented the configuration of a soft impact.

Previous Impact Studies

The impact velocity of the reactor containment system is strongly dependent on its application. In the case of the nuclear airplane, present designs are for large subsonic aircraft (ref. 1). Therefore, top impact velocities would be at 1000 to 1100 fps (ref. 2). Reactors supplying power for space stations could re-enter the atmosphere and impact at even higher speeds depending on their ballistic drag coefficients. In all of these applications it is assumed that the primary decelerator, such as parachutes, has failed to function.

Impact can occur on hard surfaces such as granite, concrete or rock or it may occur on softer surfaces such as water and soft earth. The hard surface impact will cause maximum deformation of the containment system. The soft surface impact may cause less deformation but may result in full or partial burial.

Hard Surface

Impact tests have been conducted at Sandia Corporation and Holloman AFB, New Mexico on two-foot-diameter reactor containment vessel systems weighing up to 1300 pounds (refs. 2, 3, 4, 5, and 6). These designs represented a reactor surrounded by radiation shielding and a containment vessel, both of which were designed to absorb impact energy.

The models were accelerated on a sled to speeds of 1055 fps and impacted against a reinforced concrete block weighing 18 000 pounds. Figure 1 shows a model in the before and after impact condition. The deformation of this model δ/R was measured as 0.92 (where δ is defined as the diameter of the vessel before impact minus the height of the vessel after impact and R is the vessel radius before impact).

The concrete block suffered considerable damage. Figure 2 shows a before and after photograph of the block. The model impacted the block and rested on the desert floor as shown in figure 2(b). For heat dissipation, this type of impact appears to be the most desirable since the containment vessel does not bury itself but remains exposed for radiation and convection of the heat from its surface.

Soft Surface

Impacting a soft target such as soil results in less deformation of the model. Depending on the soil properties, angle of impact and the W/A of the model (model weight to frontal area ratio) the model may be lying on the surface of the soil, partially buried, or fully buried. In

reference 7 C. W. Young has developed an empirical equation for the prediction of the amount of penetration that an impacted projectile would experience.

The soft surface model of impact then becomes the more severe case for the dissipation of afterheat from the containment vessel surface. In this case not only must the heat of convection and radiation be considered but also the amount of heat conducted into the adjacent soil.

ANALYSIS

After impact the model has sustained sufficient impact forces to destroy the coolant system. The fission products when decaying, start with high heat generation and then decay to much lower values (fig. 3). During the early hours after impact the heat generated far exceeds the amount dissipated from the containment vessel surface. Core temperatures increase until melting and vaporization can occur. The vapor transport can aid in the dissipation of the heat by moving the heat sources away from the hot spots outward, closer to the containment vessel. The molten material tends to block the downward movement of vaporized heat sources, causing the heat sources to move upward, away from the part of the vessel insulated by the ground and toward the part of the vessel most easily cooled by radiation and convection to the air.

The resultant time-temperature history depends on the design of the system. If the system has large amounts of heat absorbing material, the heat is soaked up during the initial decay period thus offsetting those high heating rates. Consequently, internal temperatures are lower. If there is little heat absorbing material the internal temperatures will increase rapidly causing rapid core melting, fission product vaporization and heat source movement.

Description of the Containment Vessel System

The reactor containment vessel system that was used as a reference design for study in this report is shown in figure 4. It is a system designed to deliver up to 300 megawatts of thermal power to a nuclear airplane. The system consists of a thermal reactor which is surrounded by gamma and neutron shielding. The shielded reactor is surrounded by a containment vessel for protection in the event of an impact. Adjacent to the surface of the containment vessel is a layer of insulation to protect the vessel from direct deposit of the fission heat sources. The insulation tends to reduce containment vessel hot spots and to increase the amount of heat stored within the vessel by increasing the average temperature of the contents in the containment vessel for any given surface temperature.

During normal operation the reactor core consists of fuel pins that are cooled by high pressure helium which is contained by pressure tubes.

Water is provided as the moderator. A typical unit designed to provide 300 megawatts thermal heat to helium at 1730° F can be enclosed inside a spherical reactor containment vessel of 20 feet outside diameter. Pertinent reactor characteristics are shown in table 1. Principal materials of construction are shown in table 2.

Description of the ESATA Program

A computer program entitled "Executive Subroutines for Afterheat Temperature Analysis" (ESATA)[8,9] was used to analyze the time-temperature history of the reference design described above. The ESATA program uses an existing TAP-A computer program[10] developed by Westinghouse. TAP-A solves problems involving transient and steady-state heat transfer in multi-dimensional systems having arbitrary geometric configurations, boundary conditions, initial conditions, and physical properties. It also has the capability of considering the following models of heat transfer and boundary conditions: internal conduction, free and forced convection, radiation of external surfaces, specified time-dependent surface temperatures, and specified time-dependent surface heat fluxes.

The computer code ESATA was formed by adding subroutines to the TAP-A code to account for the following phenomena included in this analysis:

(1) Heat source redistribution due to vapor transport of fission product from the core. The fission products transport radially outward and condense on cooler surfaces. This results in a heat source that is continuously moving away from the hot spots closer to the containment vessel.

(2) Metal - water chemical reactions within the core.

(3) Melting of the core and shield.

(4) Displacement of the core relative to the shield - containment vessel due to core-shield melting. The displacement of the core relative to the lithium hydride inner shield was assumed to occur on a component as opposed to a subcomponent basis, i.e., portions of the core region could not displace due to local melting of the lithium hydride surrounding the core but rather all of the lithium hydride beneath the core was required to be molten before core displacement occurred.

(5) Pressure build-up within the containment vessel due to vaporized fission products, metal-water reactions, and cover gases.

(6) Creep rupture analysis of the containment vessel.

In addition, the core was treated as a homogenized entity which yields an average as opposed to a peak core temperature prediction. This tends to delay the time required for the core to displace the lithium hydride and reach the innermost tungsten shield layer.

The ESATA computer code is being extended as part of an Air Force contract F29601-M2-C00035 (ref. 11) to include analysis of liquid metal fast reactor containment systems, dissociation of hydride materials that could be considered as part of the system shield, and vaporization/condensation of liquid metals.

Heat Transfer Model

A heat transfer nodal model of the reference system design is shown in figure 5. This model contains 218 internal nodes. The following basic modeling assumptions were made:

(1) Two-dimensional time-dependent analysis with line of symmetry perpendicular to soil and coexistent with core centerline

(2) No internal deformation with shield layer structure intact

(3) Piping and structural support considered as part of the reactor core from a heat capacitance standpoint

The reactor core and the inner shield region are divided into 38 cylindrical and interfacing nodes. Of the 38 nodes, those representing the core are established as part of the input to the program. The remaining nodes are used to mathematically couple the cylindrical nodes representing the core to the spherical nodes representing the remainder of the reactor containment vessel system.

Nodes 39 to 170 represent the remainder of the reactor containment system. It consists of four layers of tungsten shielding (nodes 39 to 50, 63 to 74, 87 to 98, and 111 to 122), a layer of UO_2 for insulation adjacent to the containment vessel (nodes 135 to 146), and the containment vessel (147 to 170). The remaining nodes represent LiH shielding.

Nodes 171 to 219 represent the environment. In some cases these are represented as soil conduction or they are air convection and radiation nodes. They are designated internal to the program by the degree of ground burial provided in the input.

The initial system temperatures and pressures at the time of impact for all the computations are summarized in table 3. Table 4 summarizes the weight of those components forming the reactor core. Also, included in table 4 is the surface areas of the fuel pin clad and of the pressure tubes. The radii and shield layer thicknesses are presented in table 5. All of this information is required as input to the ESATA code.

Parametric Calculations

The afterheat temperature response of the reference reactor containment vessel system described above was computed for 100, 200, and 300 mw

power levels and 33 and 50% earth burial. These computations assumed a soft impact, i.e., the undeformed model. Two modes of redistributing the fission products were examined. In the first mode the computations assumed upward movement of the fission products resulting in preferential deposition of the fission products on approximately 60% of the upward surface area. The second mode assumed condensation on a volume-weighted basis uniformly over an entire shield layer. Table 6 summarizes the cases that were calculated and specifies the mode of redistribution. All computations were terminated after 1 600 000 seconds (445 hrs) following the impact event.

RESULTS AND DISCUSSION

The data presented in this report are an initial attempt to understand the powerplant design variables that affect the post-impact survival of the system. Therefore, the results presented herein are strongly dependent on the assumptions that were part of the heat-transfer model and presented in the previous section.

Time - Temperature Response of the Containment System

The afterheat time - temperature response of the reactor containment vessel system was examined for a typical configuration using case 1 of table 6. In case 1 it was assumed that the containment vessel penetrated the soil to a depth of 50% of the diameter and the reactor was operating at 300 mw of power prior to impact. It was also assumed that the fission products - once released from the core - would rise upward and condense and re-evaporate only from the upper portion (60% of the circumference of any spherical shield layer) of the system.

Figure 6 presents representative temperatures in the core, shield, and containment vessel at various times after shutdown. At about 300 seconds, the core temperature response flattened due to the melting of the 18 000 pounds of core structure. Approximately 400 seconds were required for the core structure to completely melt. Once melting was completed, the core continued to increase in temperature to a peak value of 4800° R which occurred at about 10 000 seconds. In the 10 000 to 100 000 second time period the core decreased in temperature to about 3000° R as its heat was absorbed by the relatively cool lithium hydride surrounding the core. The core remained at a relatively constant temperature for the next 400 000 seconds as the lithium hydride surrounding the core melted and was displaced by the core as shown in figure 7. At 500 000 seconds, the core sank to the first tungsten shield layer. The core increased slightly in temperature for subsequent time period due principally to the removal of the lithium hydride sink (all lithium hydride in the core region was molten) and because the core was moving into regions of lower heat dissipation. The shield and containment vessel temperatures increased more slowly because of the time it takes the heat to reach them.

Time - Temperature Response of the Containment Vessel

Figure 8 compares the time - temperature response of the top and bottom of the containment vessel for case 1. Its upper surface temperature peaked at 880 R at about 500 000 seconds. The bottom surface temperature, although appearing to reach its peak, continues to increase to 1660° R at 1 600 000 seconds which was the termination point for all the computations. Figure 9 presents the circumferential temperature profile of the containment vessel at the 1 000 000 seconds time point in the afterheat decay transient. The temperature profile at the top and bottom is flat with a steep 800° F change in a 30 degree region between the two levels. The smaller temperature level corresponds to the section of the containment vessel that is adjacent to air and the larger temperature level corresponds to the vessel section adjacent to the soil. The steep temperature change along the vessel at the soil to air interface indicates that circumferential conduction in the containment vessel does not redistribute the heat significantly.

Heat Generated Versus Heat Dissipated

The greater the ground burial the longer the time at which the heat generated equals the heat dissipated. The amount of heat capacity of the system and the thickness of insulation adjacent to the containment vessel will also delay the time for a heat balance. The more rapid the fission products transport outward, however, the faster the time for a heat balance.

Figure 10 compares the total heat generated in the system to the heat transferred from the portion of the containment vessel exposed to the ambient air environment for case 1. The total heat generated is different from that shown in figure 3 due to the added heats of the metal-water reactions and changes of state of system materials. At 1 600 000 seconds the heat generated in the system is about equal to the heat transferred to the air. At this time increment the heat absorbed by the system components is essentially zero. The surface heat transferred is relatively constant after about 100 000 seconds. This is because a portion of the total heat generated is also being absorbed by the lithium hydride in the system and is being dissipated to the soil.

The significance of this heat balance is that the highest internal temperatures in the system peak at this point in time. The 1 600 000 second time period was chosen for the calculations so that the cases run would be near or past their point of heat balance. In addition, this long time to temperature peaking is important in that it could allow time to find the vessel and to bring additional cooling to the impact site to lower the containment vessel temperature.

Heat Dissipation

The internal heat generated by fission product decay is both absorbed by the system components and dissipated to the environment by conduction to the soil and radiated and convected to space. For case 3 at the 1 000 000 second time step the heat generated just equals that dissipated with the heat absorbed by the system components essentially zero (as in case 1 at the 1 600 000 second time step). At this time step the amount of heat that is conducted to the Earth is 8.7 kw (heat flux of 107.5 Btu/hr-ft^2) while that dissipated to air is 297 kw (heat flux of 1023 Btu/hr-ft^2). Of the heat that is dissipated to air 38 percent is by natural convection and 62 percent by radiation. A typical surface temperature of the exposed containment vessel was 859° R while that adjacent to the Earth was 1535° R.

Containment Vessel Pressure Response

Figure 11 illustrates the variation in internal pressure with time. The steep increase in internal pressure early in the transient is due to the metal - water reaction followed by a release of hydrogen. Subsequent increases in internal pressure result from vaporization at increased internal temperatures. At the peak pressure of 1045 psi, the containment vessel stress level is 20 905 psi. At the termination of the transient (1 600 000 sec) only 5 percent of the containment vessel creep rupture lifetime was consumed.

The final pressure of the containment system is also influenced by the initial pressure the system had after impact. This pressure, however, can be controlled by judicial design. Case 1 of this study used 30 psi as the helium blanket pressure of the system at the start of the post-impact period. Shield materials used within the system design can also influence the final system pressure and subsequently the containment vessel stress level. Neither the volume change due to melting or the effects of dissociation of LiH were taken into consideration. Due to the large amounts of LiH, this could increase the system pressure as shield temperatures reach the level at which dissociation occurs.

Fission Product Redistribution

The mode of fission product redistribution influences the temperature of the containment system. The two extremes in predicting how the fission products would redistribute when the core begins to melt are: (1) all fission products released from the core are uniformly distributed throughout the containment system in a 4π manner as in case 2; and (2) that all fission products released from the core move upward and condense on the surfaces that are exposed to the atmosphere with no fission products condensing on the surfaces exposed to the ground interface as in case 1. The second process was used for the model for fission product redistribution in most of the cases studied in this report as it was felt the molten

material would tend to block the downward movement of the fission products. Case 2, however, was run to determine the effect of the two extremes in fission product redistribution modeling.

Figure 12 presents the surface temperature response of the top and bottom of the containment vessel for cases 1 and 2. The surface temperatures performed as expected. When the fission products plated uniformly, the bottom surface temperature of the containment vessel were in excess of 1800° R and still increasing at the 1 600 000 second calculation time increment. This was due to the heat sources that were deposited in that area. When the fission products plated preferentially, i.e., in the upper portion of the containment system, the bottom surface temperatures ran cooler - less than 1700° R and peaking out. This was due to the absence of fission product heat sources in that area.

For the top surface temperatures, when the preferential plating occurred, more fission products (heat sources) were deposited in this area, thus the surface temperature was higher. When a uniform plating occurred less fission products were in the area due to those that plated in other areas of the system - thus the surface temperature was lower.

Influence of Reactor Operating Power Level and Degree of Burial

The influence of the reactor operating power level on the containment vessel temperature response is presented in figures 13 and 14 for soil penetration depths of 50 percent (cases 1, 4, and 6) and 33 percent (cases 3, 5, and 7). The depth of burial had little influence on the time for temperature peaking or on the peak temperature level for the cases considered. For 100 to 300 mw power levels, the temperature of the exposed (top) portion of the containment vessel peaked in the 100 000 to the 1 000 000 second time period at a temperature less than 900° R. The time that the peak temperature was reached increased with increasing power level. The temperatures of the buried portion of the containment vessel reached about 1200° to 1700° R for powers of 100 to 300 mw and tended to reach temperature plateaus during the transient. This is because the total heat generated by the system is being absorbed due to melting of the internal components, i.e., principally the lithium hydride shield layers. The sudden increase in temperature at about 500 000 seconds occurred because of the completion of melting of a large fraction of the lithium hydride in the system.

Figure 15 presents the containment vessel temperature as a function of power level at 1 600 000 seconds following impact. At the containment vessel bottom, a 50 percent Earth burial as opposed to a 33 percent Earth burial resulted in about a 140° F containment vessel temperature difference at a 100 mw reactor power level and about 60° F for the 300 mw power level. Also, lowering the reactor power level from 300 to 100 mw results in a 400° F decrease in the temperature for the buried portion of the containment vessel.

CONCLUDING REMARKS

Small nuclear powerplants used as the power supply for mobile vehicles are subject to high speed impact accidents. In the event that this accident occurs the afterheat of the decay of fission products must be removed to prevent the melting of the containment vessel and the release of fission products. With the loss of the coolant system due to the impact accident the heat must be transferred through the containment vessel and into the surrounding environment.

A computer program entitled "Executive Subroutines for Afterheat Temperature Analysis" (ESATA) was used to analyze the time - temperature response during the post-impact period of a system designed to deliver up to 300 mw of thermal power to a nuclear airplane. This analysis considers in addition to conduction, radiation, and convection, the heats of fusion, vaporization, and material movement due to the melting and resolidification of the core. Also, the process of the fission products' vaporizing and convecting upward to condense on cooler surfaces is considered.

Seven cases were computed and their data presented. The results are summarized as follows:

1. The temperature response of the containment system is noticeably affected by the melting of the core and the heat absorption of the shield material.

2. When the fission products plated preferentially, i.e., in the upper portion of the containment system the bottom surface temperatures ran cooler - less than 1700° R and were peaking out.

3. When the fission products plated uniformly the bottom surface temperatures of the containment vessel were in excess of 1800° R thus, convection is an important transport mechanism limiting the peak temperatures.

4. Lowering the reactor power level from 300 to 100 mw results in a 400° F decrease in the temperature for the buried portion of the containment vessel.

5. The time required to reach the peak containment vessel temperature following the impact event could potentially be in excess of 1 600 000 seconds (445 hrs).

6. Increasing the degree of soil burial from 33 to 50 percent of the containment vessel diameter increases the vessel temperature by about 100° F at a 100 mw power level and by about 60° F at 300 mw but does not change the time to peak temperature, significantly.

7. The maximum peak containment vessel temperature calculated was 1660° F and occurred for the 300 mw, 50 percent burial, 60 percent fission product redistribution case. This temperature is within the material limits for 304 stainless steel.

8. For a typical case at the 1 000 000 second time increment, 38 percent of the heat was dissipated by natural convection, 62 percent by radiation, and less than 2 percent conducted to the Earth.

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TABLE 1. - REACTOR CHARACTERISTICS

Reactor power, MW	100 to 300
Reactor inlet pressure, psi	1500
Reactor inlet temperature, F	1000
Operating lifetime, hr	10 000
Active reactor core, diam in.	66
Active reactor core, length in.	42
Reactor shut down pressure, psi	30

TABLE 2. - MATERIALS OF CONSTRUCTION

Fuel element clad	Molybdenum Alloy TZM
Fuel element supports	Hastelloy X
Pressure tube layers	Hastelloy X, Min-K 2000 and Austenitic Steel (AM-355)
Pressure vessel	Austenitic Steel (AM-355)
Shielding	Tungsten, LiH
Containment vessel	Stainless Steel (316)
Insulation	UO_2
Moderator	Water (all but 300 lb removed prior to impact)

TABLE 3. - INITIAL TEMPERATURES AND PRESSURES

	Temperature, °R
Clad and fuel	2310
Structure	1660
Water	672
Shield	1260
Containment vessel	560
Ambient	560

Internal pressure 30 psi

TABLE 4. - CORE MASS AND AREA

	Mass, lb
Molybdenum	8 130
UO_2 in core	1 914
Pressure vessel and support structure	17 939
Water left in core	300
	Area, in.^{2}
Pressure tube surface area	113 000
Clad area	303 000

TABLE 5. - KEY RADII AND THICKNESSES

Overall core radius, in.	35
Overall core height, in.	53

	Inner radius, in.	Thickness, in.
Shield layers		
First layer	54	2.5
Second layer	60	1.5
Third layer	70	1.0
Fourth layer	85	1.0

UO_2 insulation thickness, in.	4.0
Containment vessel inner radius, in.	120
Containment vessel thickness, in.	3

TABLE 6. - SUMMARY OF PARAMETRIC CALCULATION PARAMETERS

Parameter	Case						
	1	2	3	4	5	6	7
Power level, MW	300	300	300	200	200	100	100
Degree of burial, %	50	50	33	50	33	50	33
Fission product redistribution, %	60	100	60	60	60	60	60

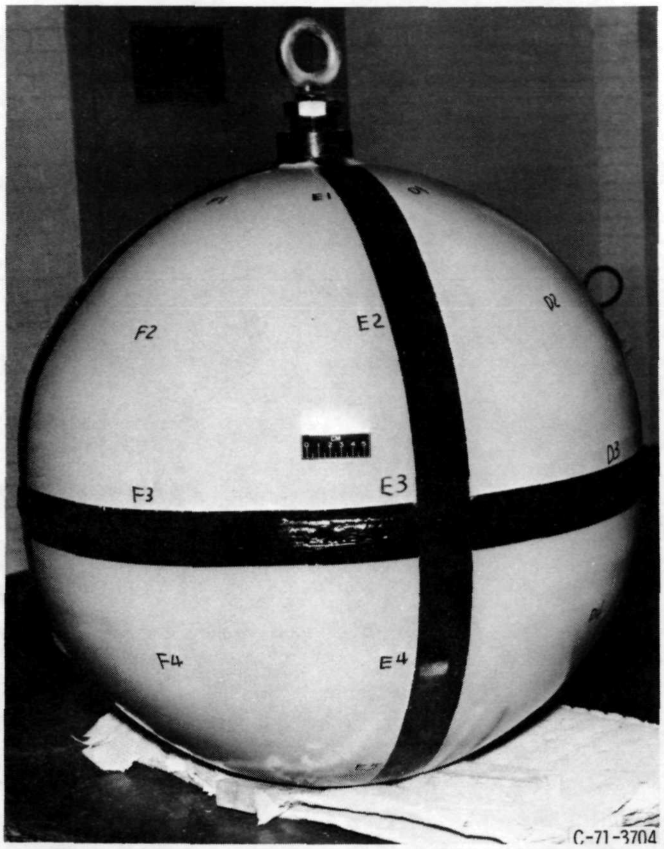

Figure 1(a). - Nuclear containment system - before impact.

Figure 1(b). - Nuclear containment system - after impact.

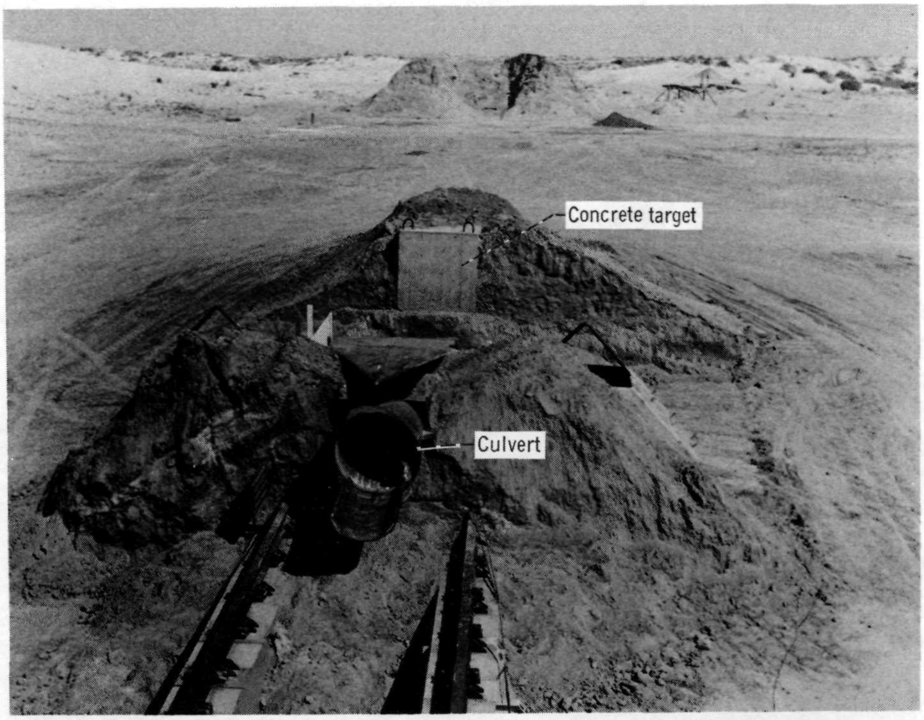

Figure 2(a). - Concrete target - before impact.

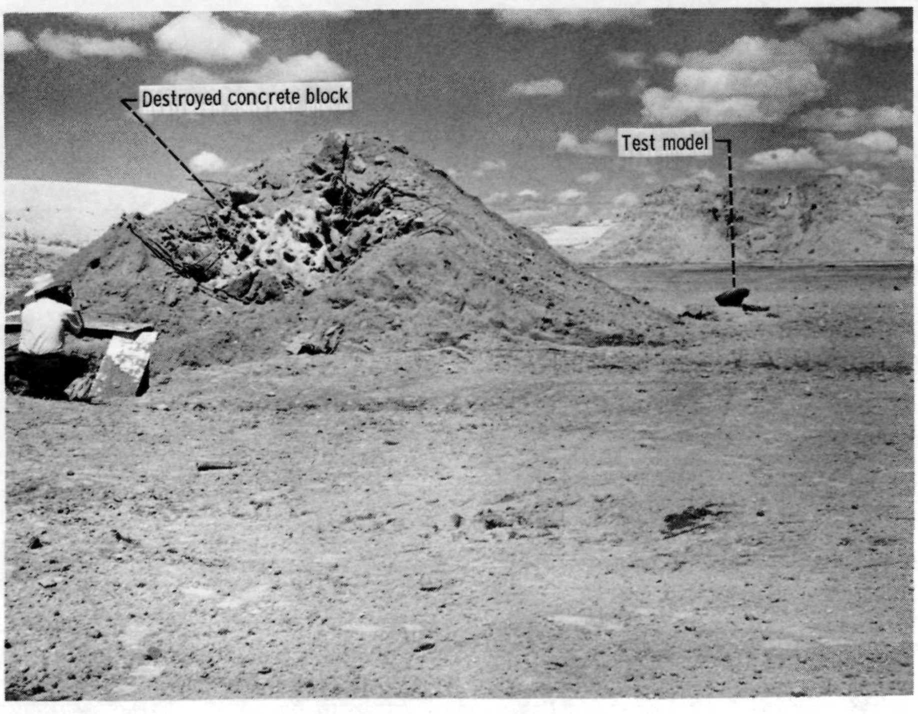

Figure 2(b). - Concrete target - after impact.

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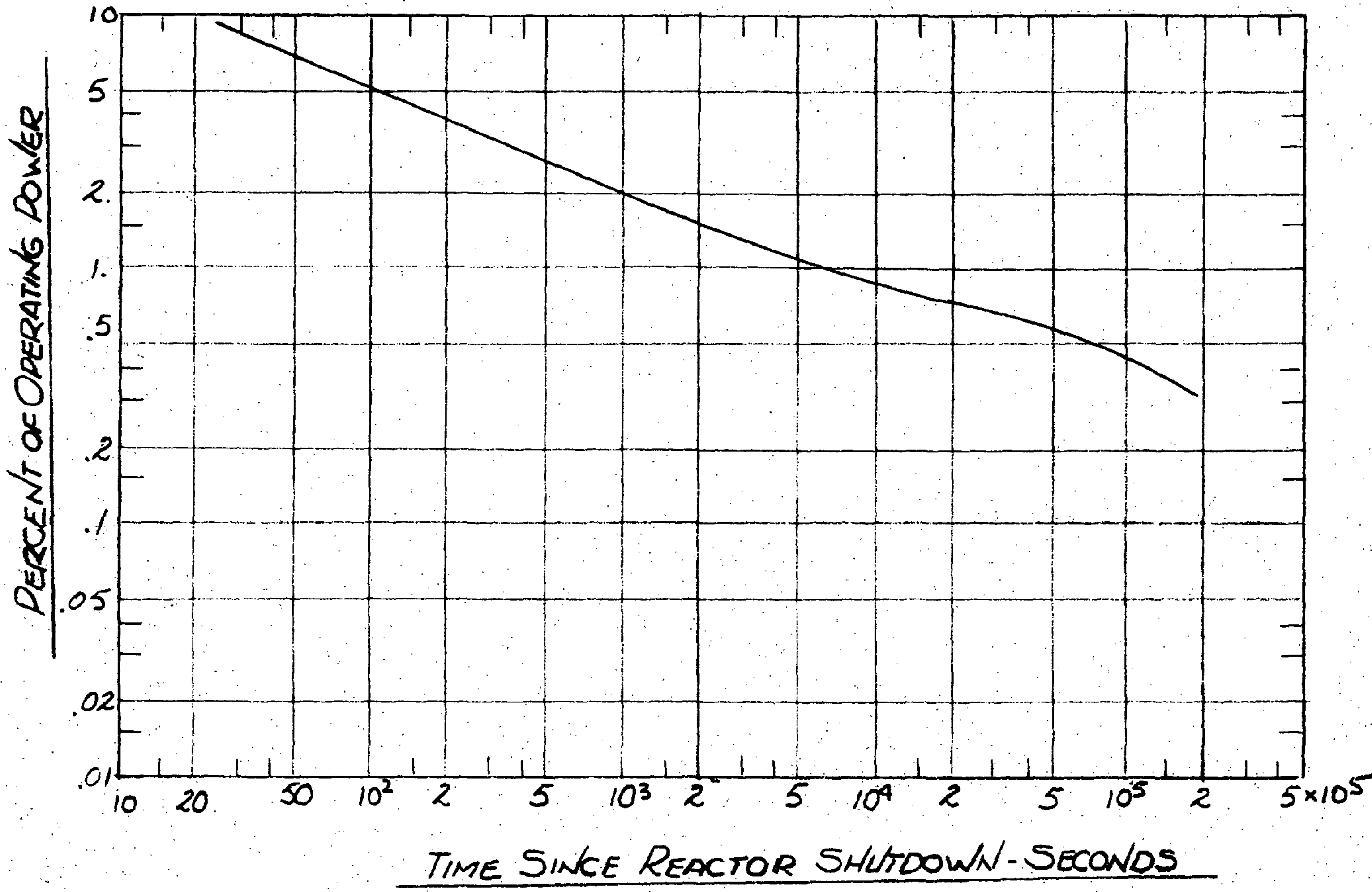


FIG. 3: FISSION PRODUCT DECAY HEAT

NUCLEAR AIRCRAFT REACTOR, SHIELD & CONTAINMENT VESSEL

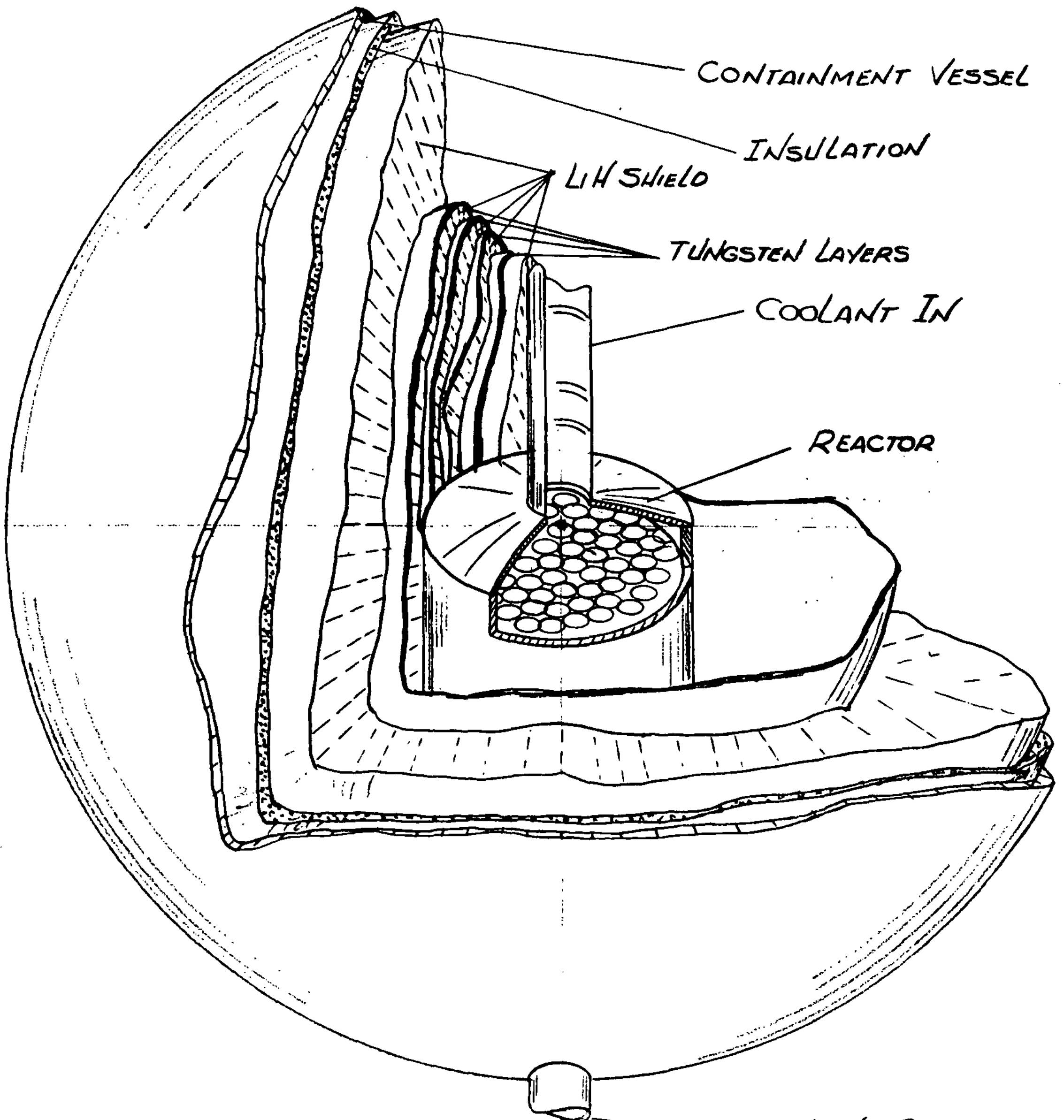


FIG 4:

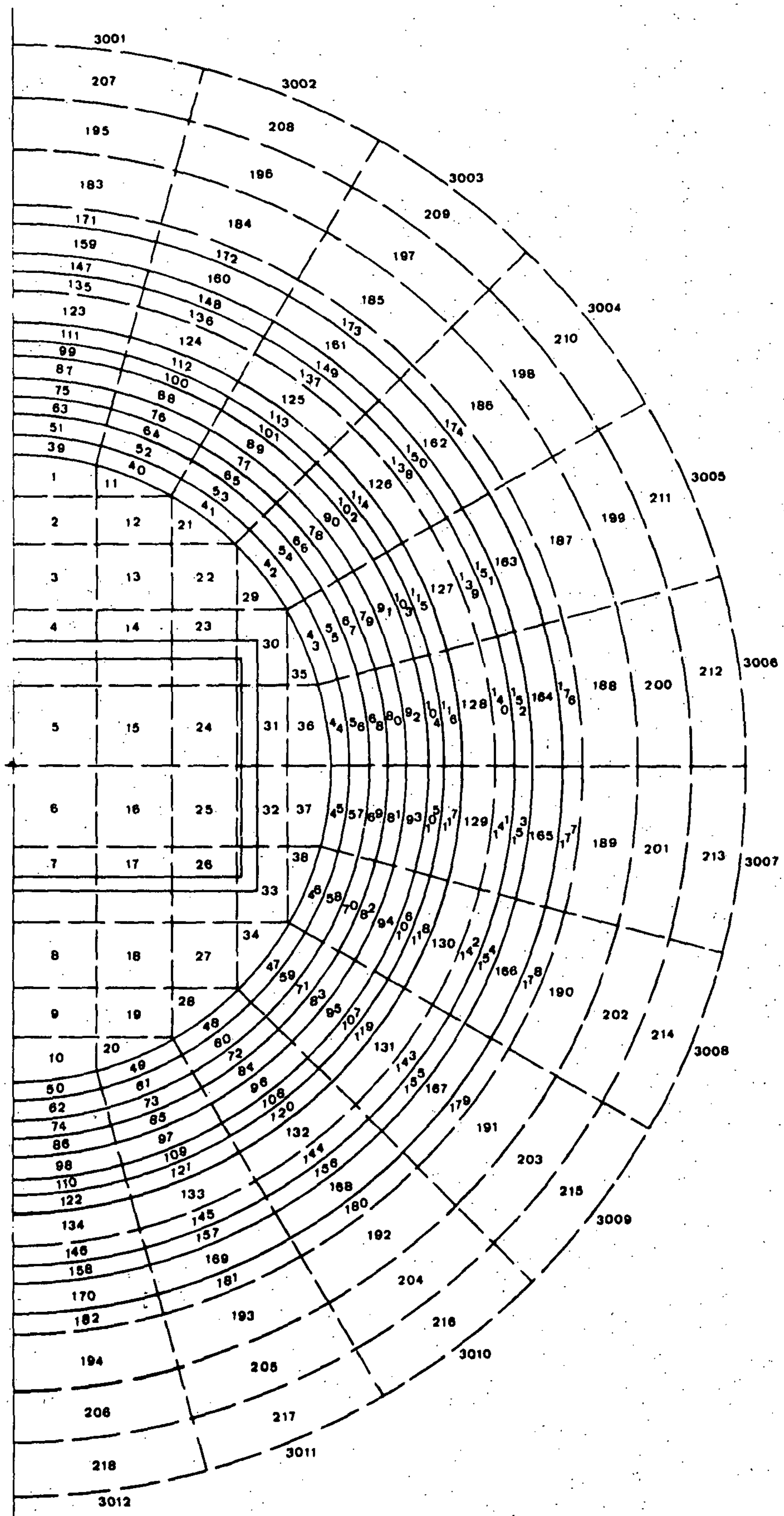


Figure 5. - Heat transfer nodal model.

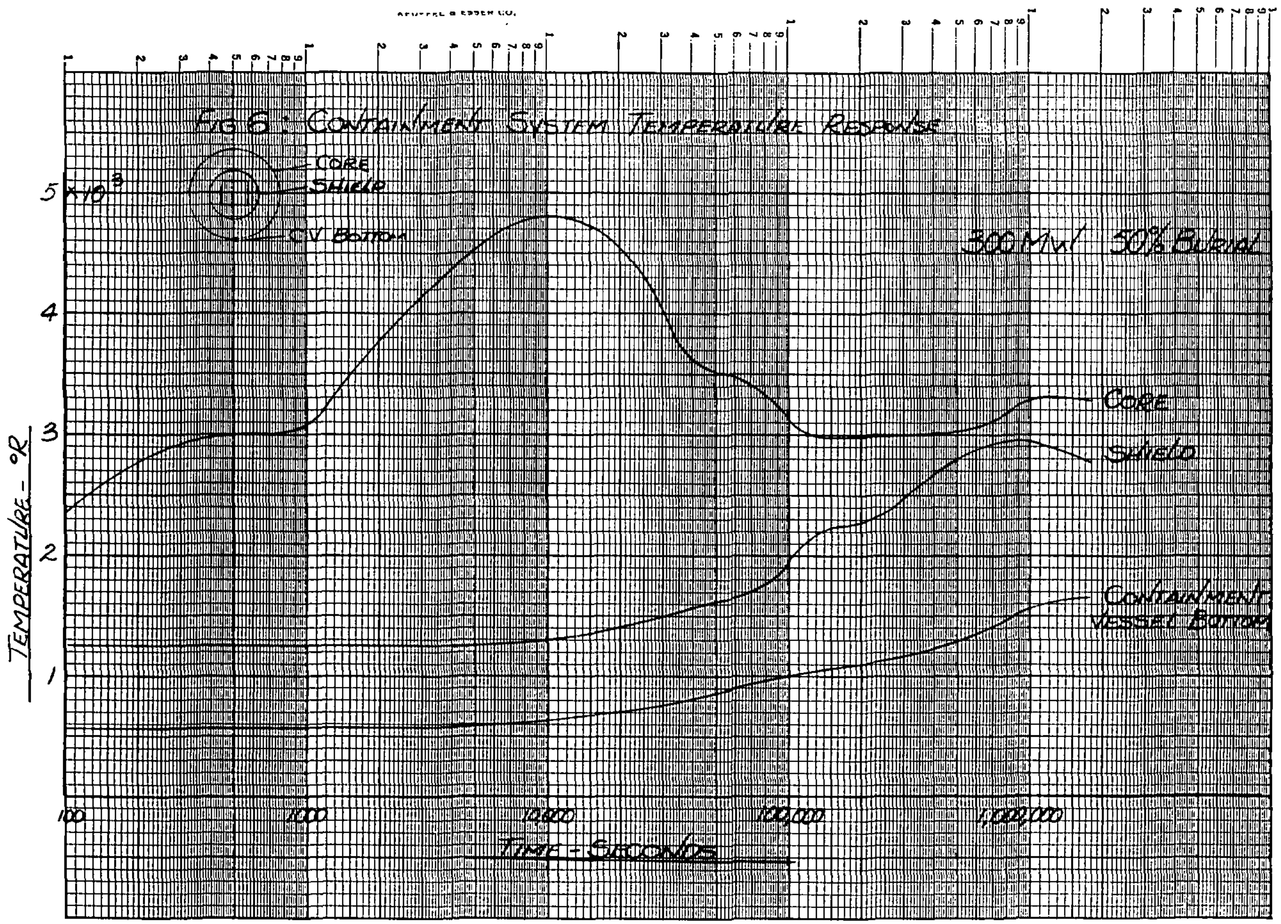


FIG 6: CONTAINMENT SYSTEM TEMPERATURE RESPONSE
CORE
SHIELD
CV BOTTOM
300 MW 50% BURIAL
5 x10^3
4
3
2
1
TEMPERATURE - °R
CORE
SHIELD
CONTAINMENT VESSEL BOTTOM
100
1000
10,000
100,000
1,000,000
TIME - SECONDS

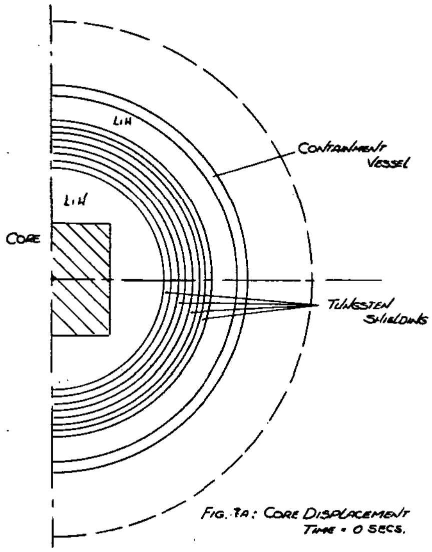


Fig. 7a: Core Displacement
Time = 0 Secs.

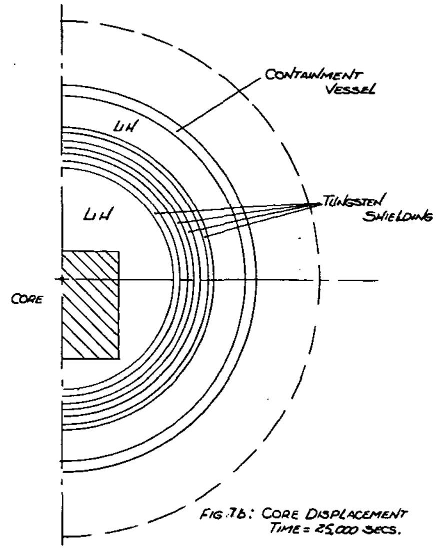


Fig. 7b: Core Displacement
Time = 25,000 Secs.

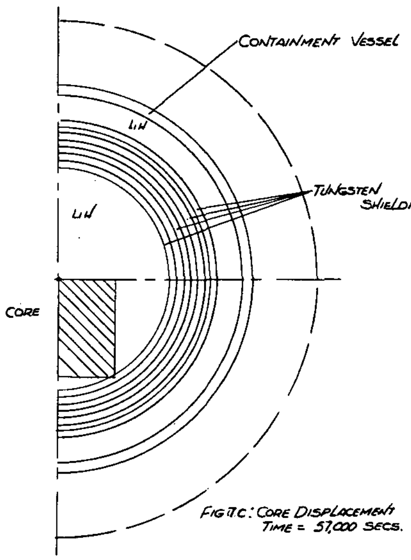


Fig. 7c: Core Displacement
Time = 57,000 Secs.

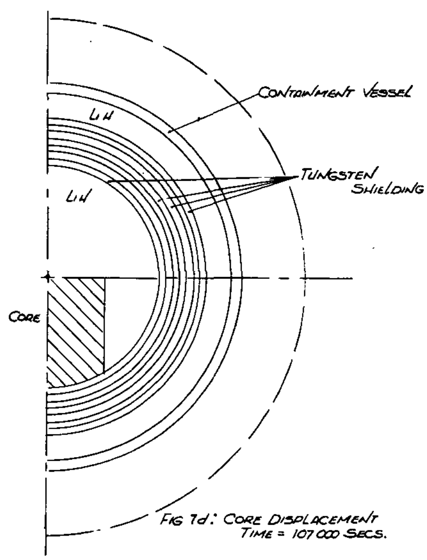


Fig. 7d: Core Displacement
Time = 107 000 Secs.

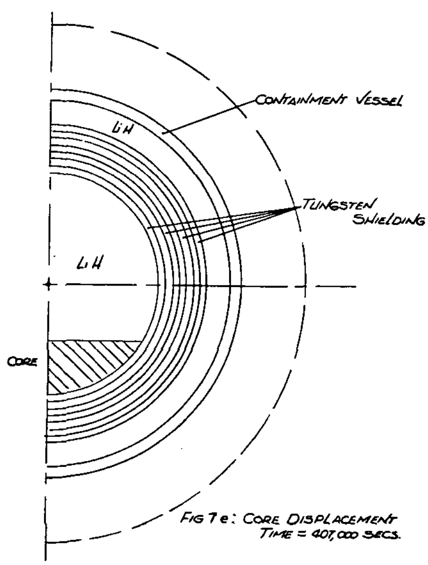
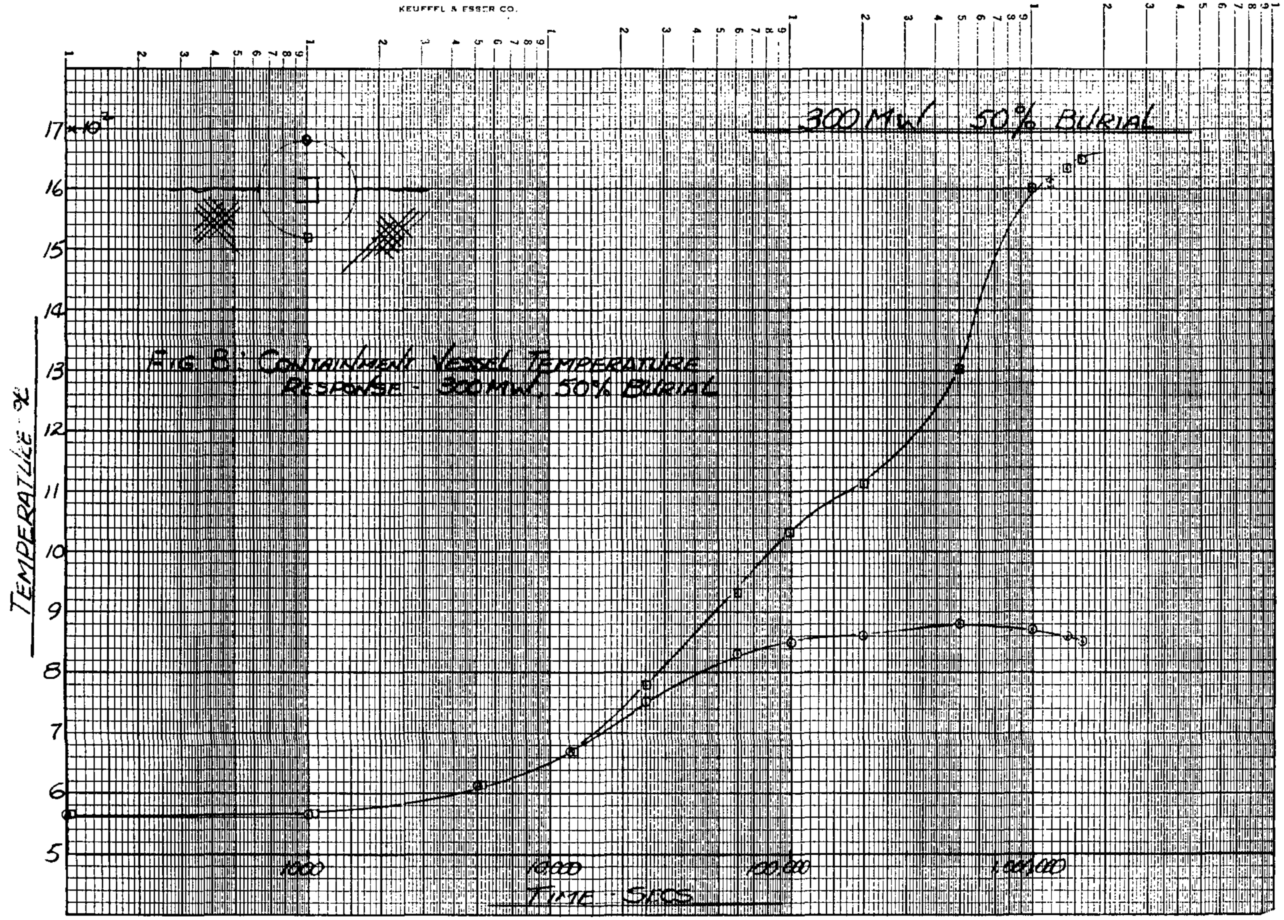


Fig. 7e: Core Displacement
Time = 407,000 Secs.


KEUFFEL & ESSER CO.
300 MW 50% BURIAL
FIG. 8: CONTAINMENT VESSEL TEMPERATURE RESPONSE - 300 MW, 50% BURIAL
TEMPERATURE °K
17×10²
16
15
14
13
12
11
10
9
8
7
6
5
1000
10000
100000
1000000
TIME - SECS

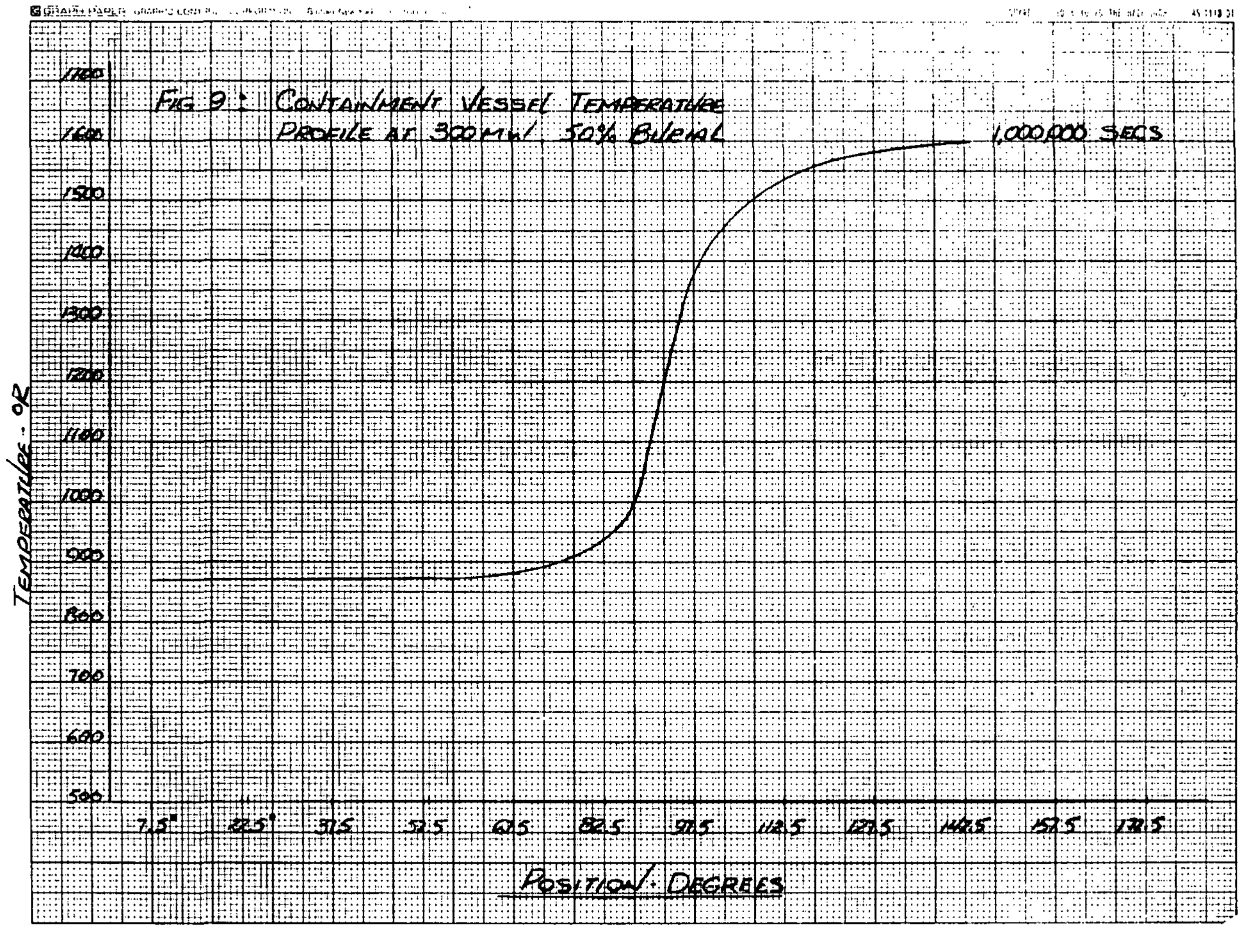


FIG 9 : CONTAINMENT VESSEL TEMPERATURE
PROFILE AT 300MW 50% BURIAL
1,000,000 SECS
TEMPERATURE - °R
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
7.5°
22.5°
37.5
52.5
67.5
82.5
97.5
112.5
127.5
142.5
157.5
172.5
POSITION - DEGREES

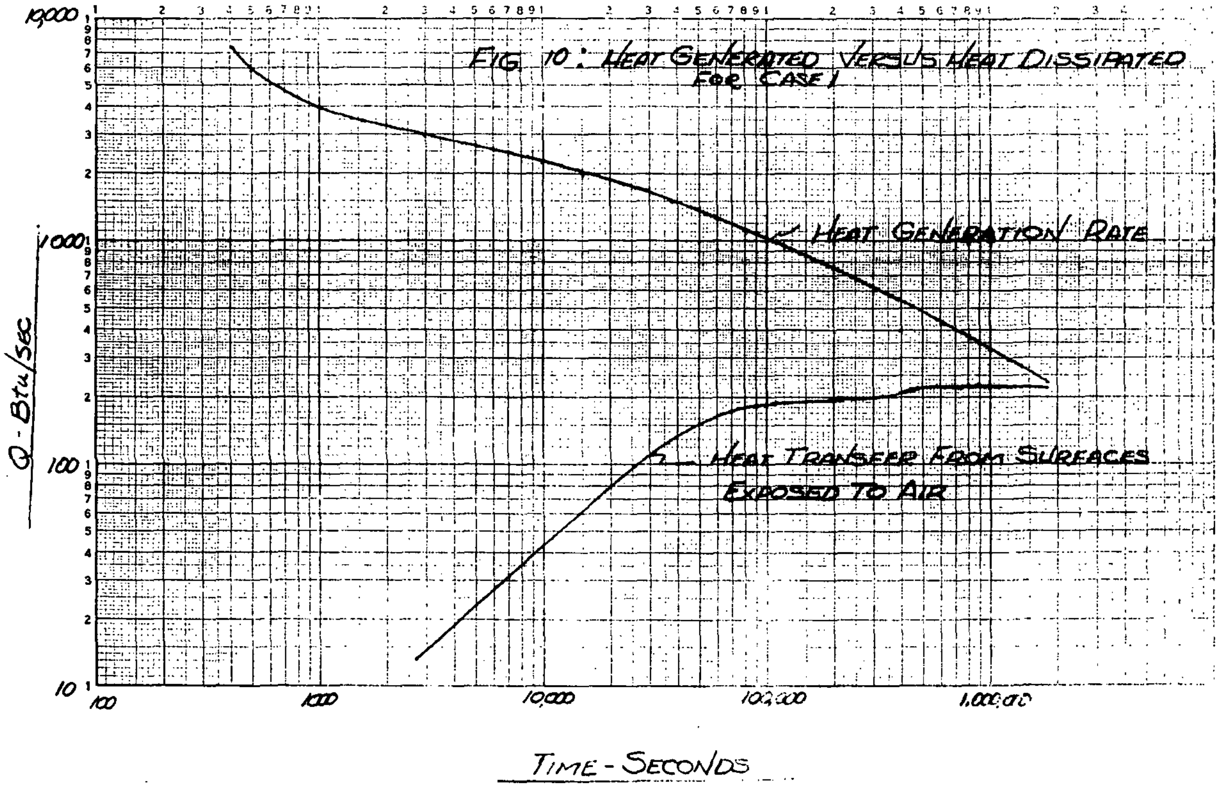


FIG. 10: HEAT GENERATED VERSUS HEAT DISSIPATED FOR CASE 1
HEAT GENERATION RATE
HEAT TRANSFER FROM SURFACES EXPOSED TO AIR
Q - Btu/SEC
10,000
1000
100
10
100
1000
10,000
100,000
1,000,000
TIME - SECONDS

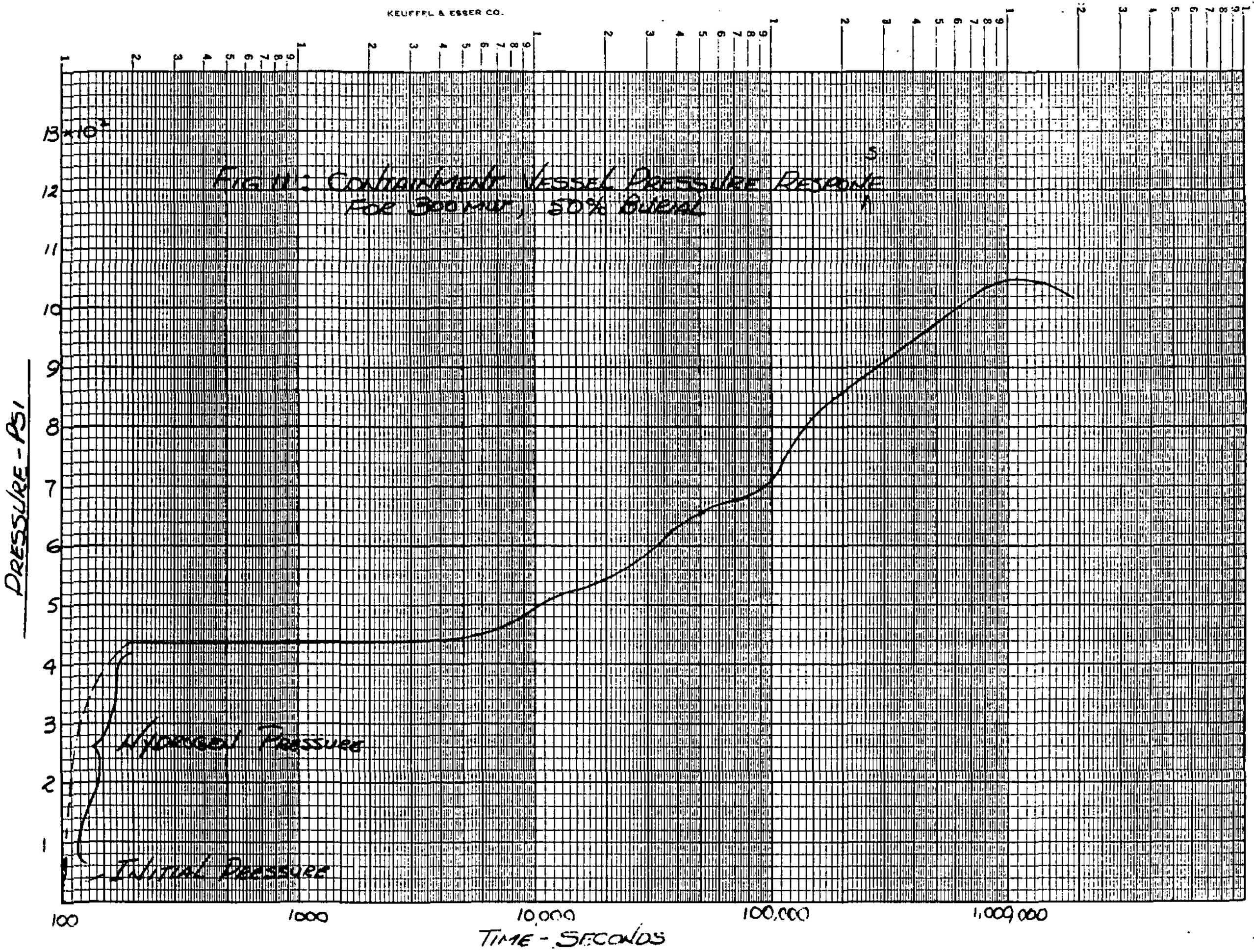
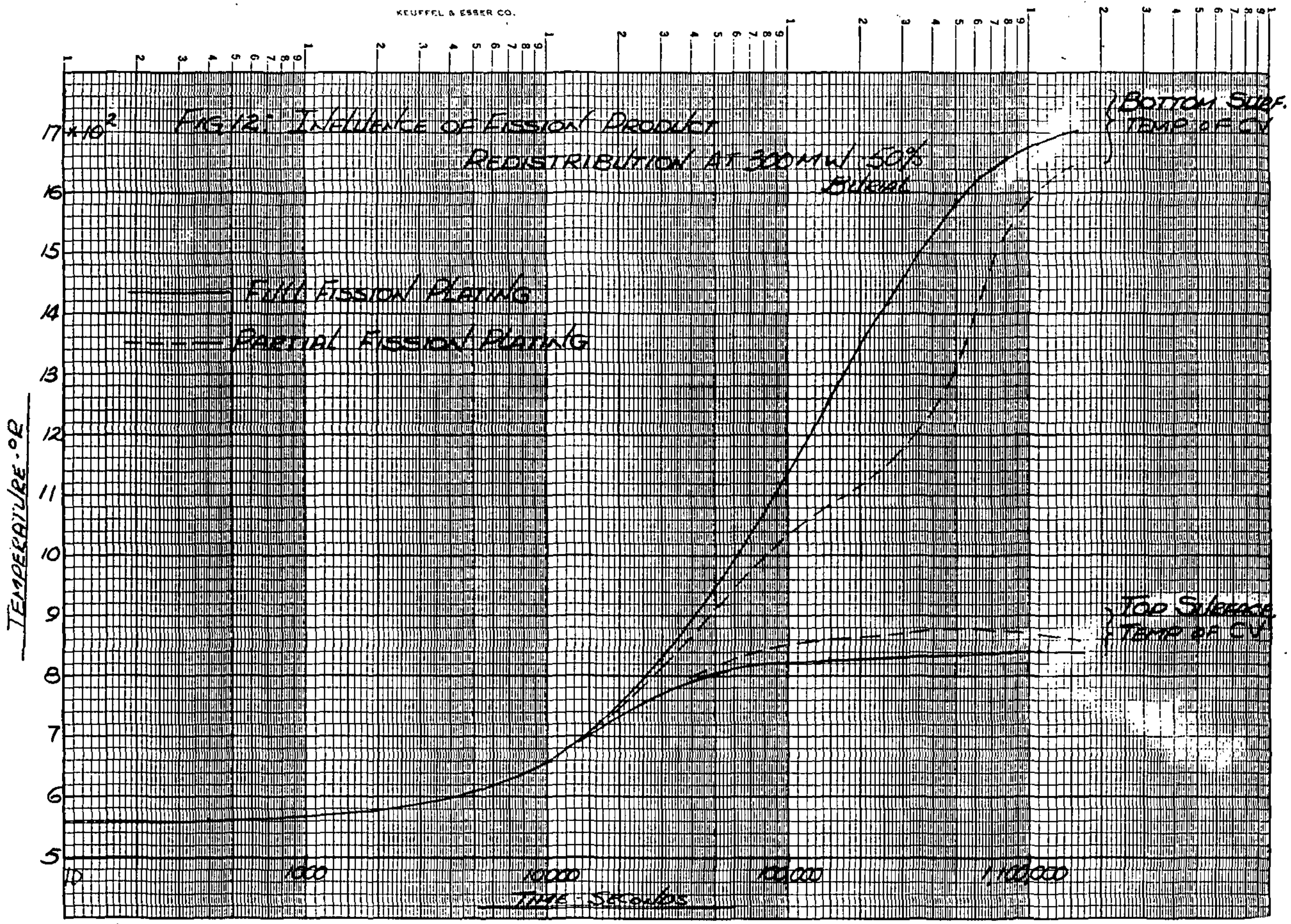


FIG 11: CONTAINMENT VESSEL PRESSURE RESPONSE
FOR 300 MW, 50% BURIAL


KEUFFEL & ESSER CO.
FIG. 12: INFLUENCE OF FISSION PRODUCT REDISTRIBUTION AT 300 MW 50% BURNUP
FULL FISSION PLATING
PARTIAL FISSION PLATING
BOTTOM SURF. TEMP OF CV
TOP SURFACE TEMP OF CV
17×10²
16
15
14
13
12
11
10
9
8
7
6
5
TEMPERATURE °R
10
1000
10,000
100,000
1,000,000
TIME SECONDS

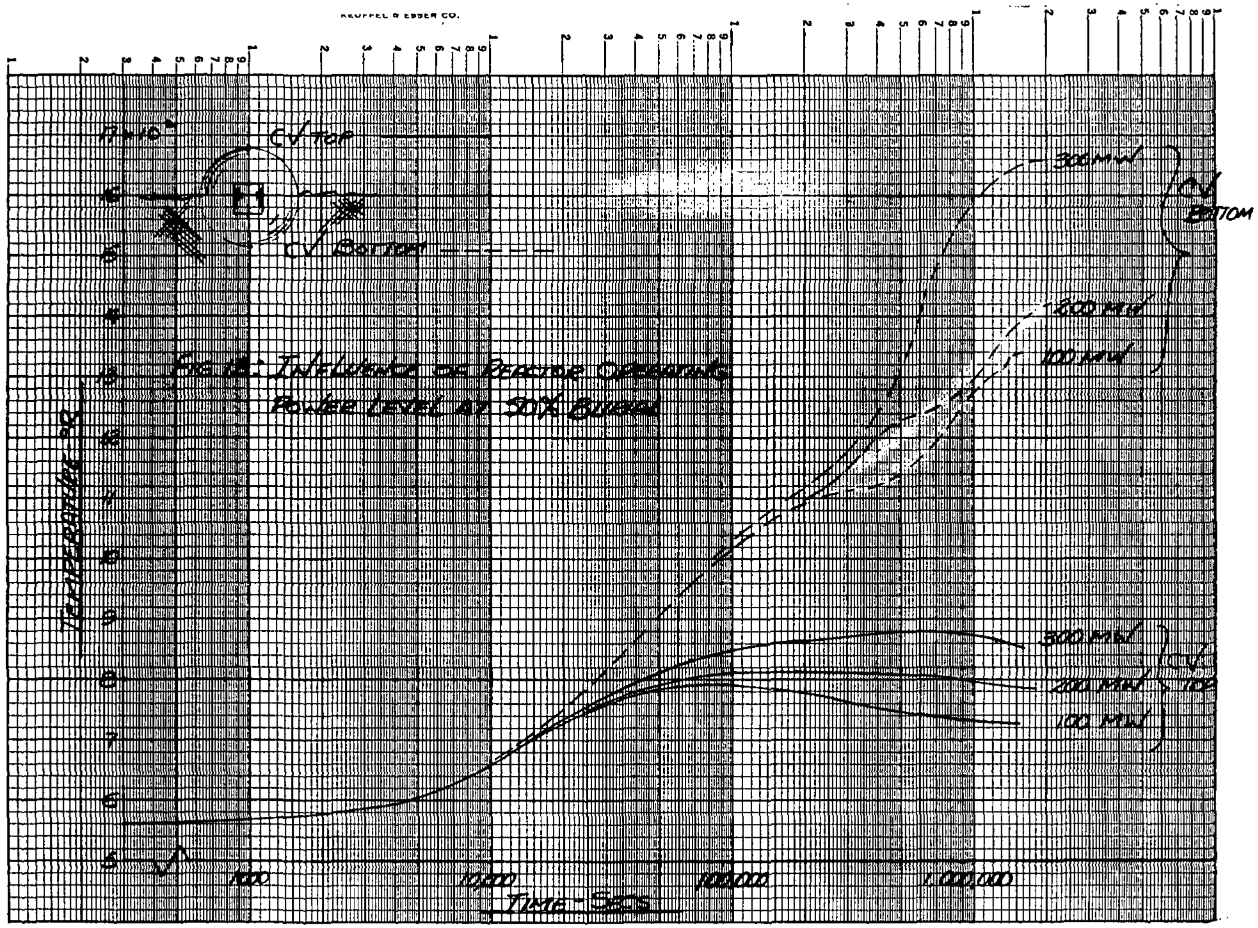
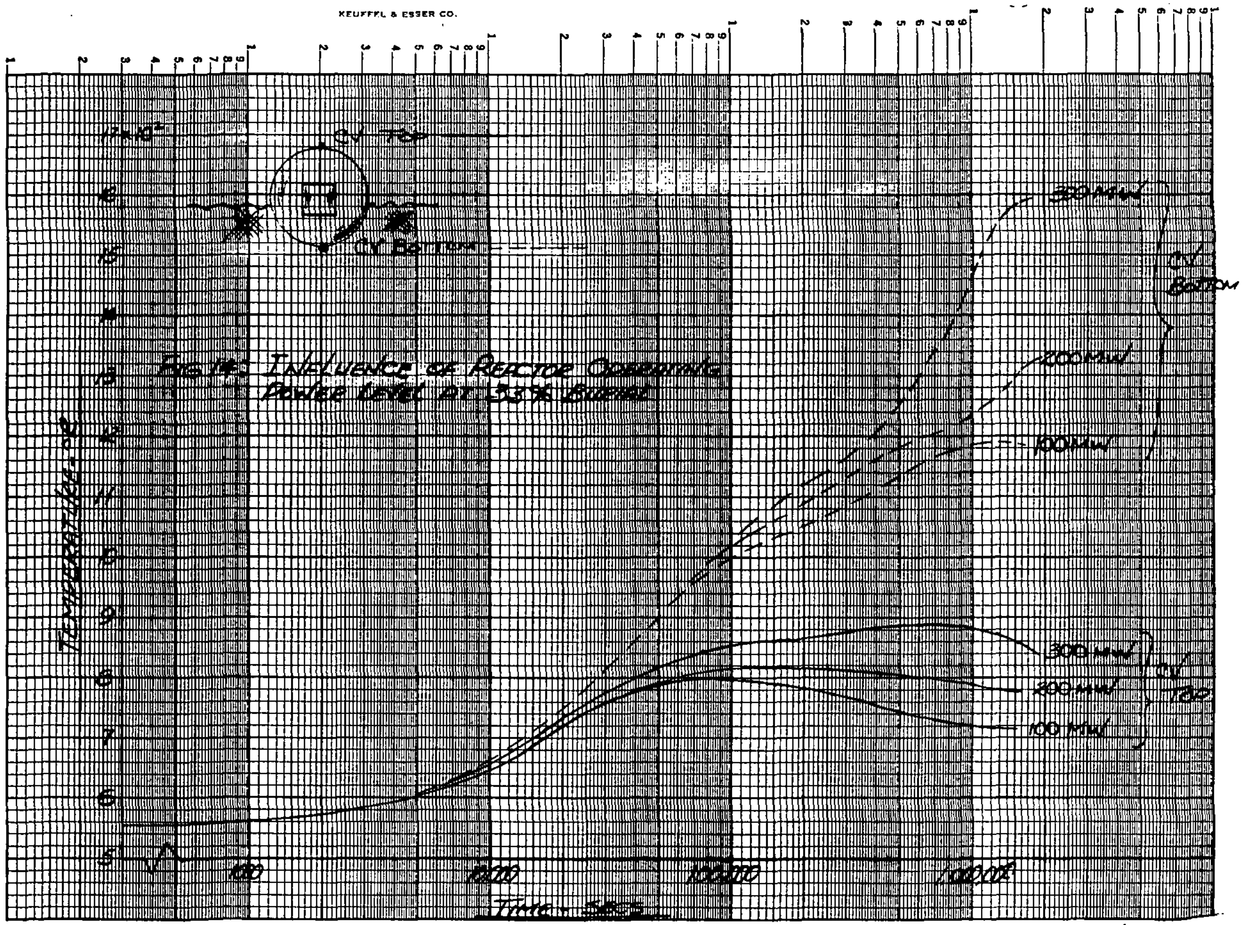


FIG. 12: INFLUENCE OF REACTOR OPERATING POWER LEVEL AT 50% BURNUP


KEUFFEL & ESSER CO.
FIG 14: INFLUENCE OF REACTOR OPERATING POWER LEVEL AT 33% BURNUP
17×10²
16
15
13
12
11
10
9
8
7
6
5
TEMPERATURE - °F
CV TOP
CV BOTTOM
300 MW
200 MW
100 MW
CV BOTTOM
300 MW
200 MW
100 MW
CV TOP
100
1000
10,000
100,000
TIME - SECS

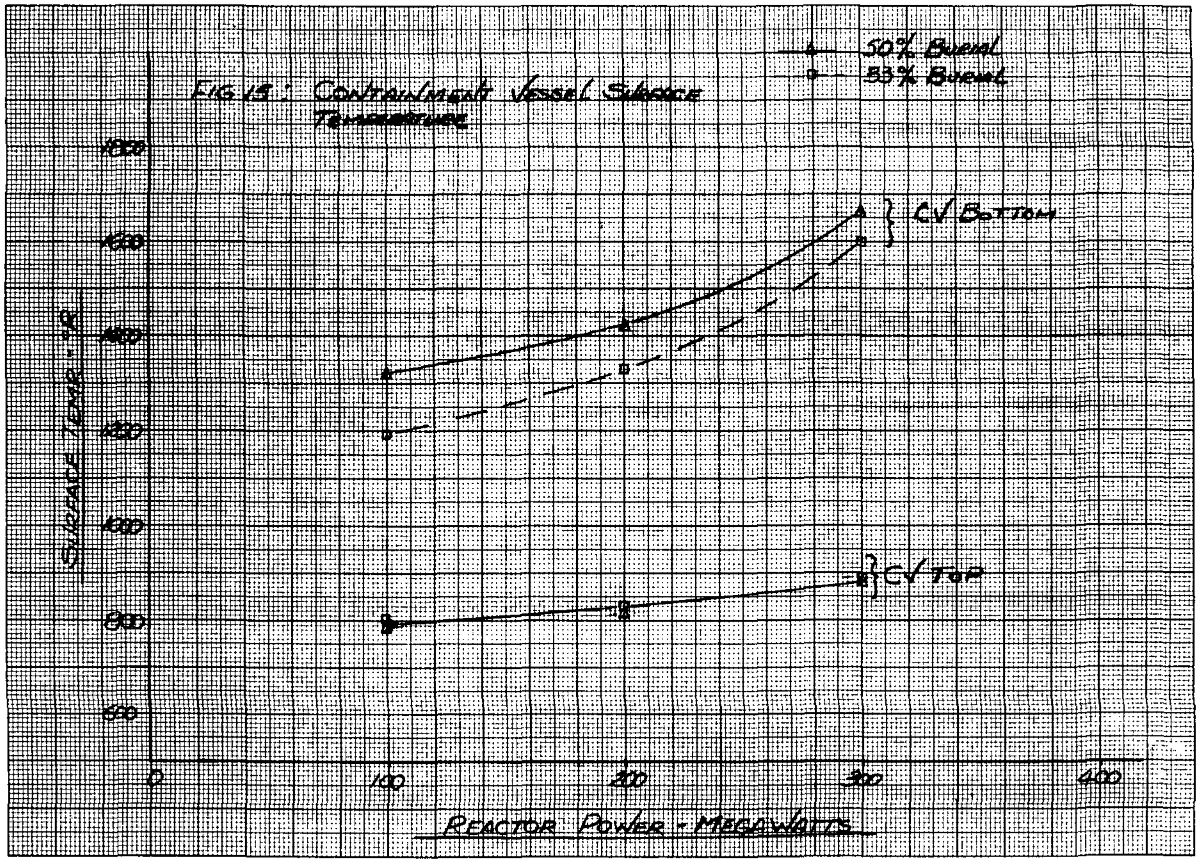


FIG 15: CONTAINMENT VESSEL SURFACE TEMPERATURE
50% BURIAL
53% BURIAL
CV BOTTOM
CV TOP
SURFACE TEMP - °R
1800
1600
1400
1200
1000
800
600
0
100
200
300
400
REACTOR POWER - MEGAWATTS